Terra MODIS RSB On-Orbit Calibration and Performance: Four Years of Data

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ABSTRACT

Terra MODIS, also referred to as the MODIS Protoflight Model (PFM), was launched on-board the NASA's EOS Terra spacecraft on December 18, 1999. It has been in operation for more than four years and continuously providing the science community quality data sets for studies of the Earth's land, oceans, and atmosphere. It has also served as the primary source of information for the MODIS Land Rapid Response System for observing and reporting on natural disasters, and providing active fire information around the Earth. The MODIS instrument has 36 spectral bands with wavelengths ranging from 0.41µm to 14.5µm: 20 bands with wavelengths below 2.2µm are the reflective solar bands (RSB) and the other 16 bands are the thermal emissive bands (TEB). The RSB are calibrated on-orbit using a solar diffuser (SD) with the degradation of its bi-directional reflectance factor (BRF) tracked by an on-board solar diffuser stability monitor (SDSM). The calibration coefficients are updated via Look-Up Tables (LUTs) for the Level 1B code that converts the sensor's Earth view response from digital counts to calibrated reflectance and radiance. In this paper we review the MODIS RSB on-orbit calibration algorithm and the methodology of computing and updating the calibration coefficients determined from the SD and SDSM data sets. We present examples of the sensor's long-term and short-term stability trending of key RSB calibration parameters using over four years of on-orbit calibration data sets. Special considerations due to changes in instrument configuration and sensor response are also discussed.

Keywords: MODIS, reflective solar bands, calibration, solar diffuser, solar diffuser stability monitor

1. INTRODUCTION

The MODerate Resolution Imaging Spectroradiometer (MODIS), one of the key instruments of the NASA Earth Observing System (EOS), is currently operating on both the Terra and Aqua satellites launched on December 18 1999 and May 4 2002 respectively[1-3]. The instrument is capable of observing the entire Earth in approximately two days via 36 spectral bands with wavelengths ranging from 0.41 µm to 14.5 µm and nadir instantaneous fields of view (IFOV) of 250m, 500m and 1km. Its design and development are extensions of other space-borne sensors such as the Advanced Very High Resolution Radiometer (AVHRR), the Nimbus-7 Coastal Zone Color Scanner (CZCS), the Landsat Thematic Mapper (TM), and the CZCS/SeaWiFS series. The two MODIS instruments provide continuous and complementary observations of the Earth with Terra orbiting in a near Sun-synchronous polar orbit of 10:30 AM local equator crossing time and Aqua in an orbit of 1:30 PM local equator crossing time. Each sensor views the Earth over a ±55° range of scan angles about instrument nadir, producing a swath 10 km (at nadir) along track and 2330 km cross-track each 1.478 second scan.

The twenty MODIS spectral bands with wavelengths below 2.2µm are the reflective solar bands (RSB) and the other 16 bands are the thermal emissive bands (TEB). The RSB are calibrated on-orbit using a solar diffuser (SD) with the degradation of its bi-directional reflectance factor (BRF) tracked via a on-board solar diffuser stability monitor (SDSM).

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Figure 1 shows the MODIS scan cavity and the RSB on-board calibrators; the SD and SDSM. The MODIS Level 1B (L1B) primary product from the RSB observations is the Earth view reflectance factor at the top of the atmosphere (TOA). In this paper we present a brief review of the current MODIS RSB calibration algorithm and the approaches for computing and updating the calibration coefficients. We show the Terra MODIS RSB on-orbit calibration results from 4 years of on-orbit data. We also illustrate trends in instrument response stability at different wavelengths under several operational scenarios; changes of the response versus scan angle (RVS); and degradation of the solar diffuser.

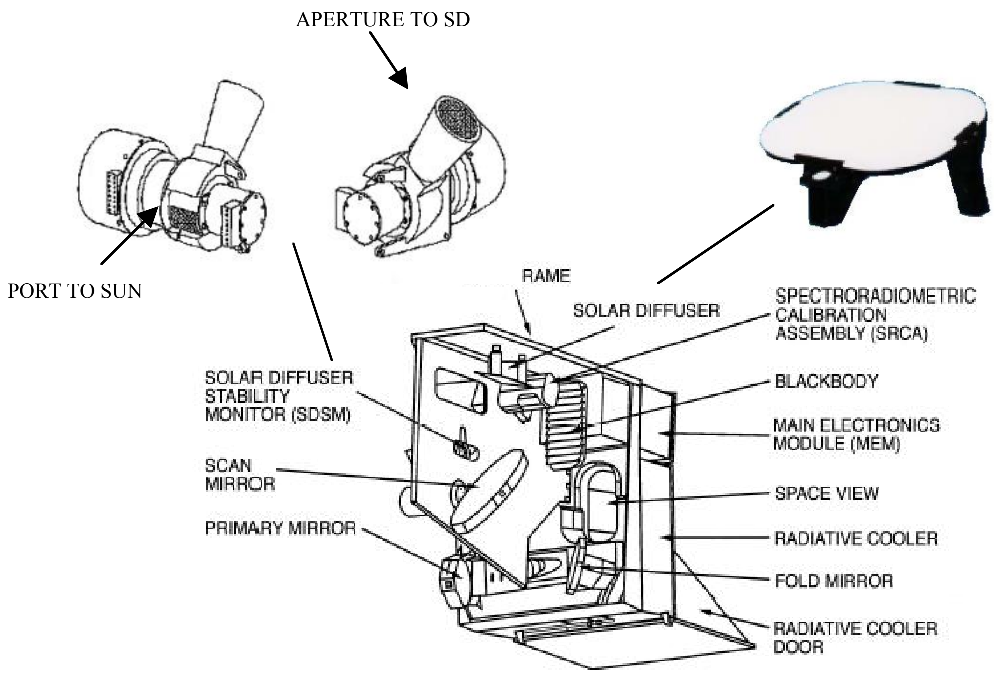

Figure 1. MODIS scan cavity and the RSB on-board calibrators: solar diffuser (SD) and solar diffuser stability monitor (SDSM).

2. REFLECTIVE SOLAR BAND CALIBRATION

2.1 RSB Calibration Using the Solar Diffuser

On-orbit calibration of the MODIS reflective solar bands (RSB) is performed using its on-board solar diffuser (SD) panel[3-5]. The MODIS Level 1B (L1B) algorithm converts the digital numbers (DNs) from the sensor to radiometrically calibrated data products. For the RSB, each Earth view frame DN is converted to a TOA reflectance factor (the primary RSB product) using time varying LUTs. These LUTs are based on and updated via extensive off-line calibration data analyses. Regularly scheduled solar diffuser (SD) observations (weekly at the beginning of the mission and biweekly afterwards) are used to derive the LUT coefficients in conjunction with an on-board solar diffuser stability monitor (SDSM) that tracks the degradation of the SD bi-directional reflectance factor (BRF). The SD is a pressed plate of Spectralon™ that is located behind a deployable door on the along-track wall of the MODIS instrument mainframe. During calibration the SD door is opened and the MODIS detectors view the near Lambertian light reflected off the SD via a scan mirror and other optics. The same optical path is used for the Earth view observations except at different angles of incidence (AOI) to the scan mirror. Because of this, the RSB response must be corrected using the sensor's response versus scan-angle (RVS). The high gain bands (B8-B16) saturate when they view the SD; therefore, the solar illumination needs to be attenuated. This is accomplished using a deployable screen located at the door aperture as shown in Figure 2. Cold space is viewed each scan by MODIS via the rotating scan mirror. The space view supplies the instrument background signal and is the second point required for the RSB linear calibration.

The Earth view reflectance factor, $\rho_{EV} \cdot \cos(\theta_{EV})$, is computed in the L1B algorithm by

$$\rho_{EV} \cdot \cos(\theta_{EV}) = m_1 \cdot dn^*_{EV} \cdot d^2_{E-S} \tag{1}$$

where m_1 is the calibration coefficient, dn^*_{EV} is the Earth view digital response, DN_{EV}, corrected for background signal, instrument temperature effect, and sensor response versus scan angle (RVS), and $d_{E\text{-}S}$ is the Earth-Sun distance at the time of the Earth observation.

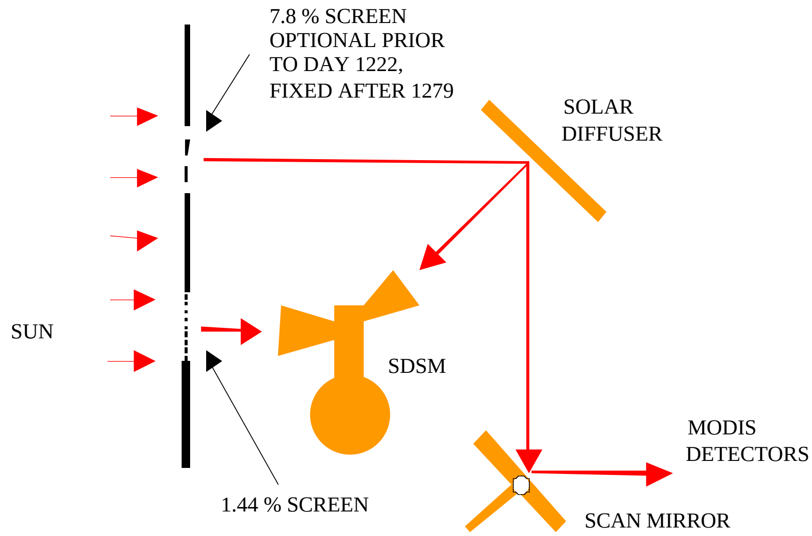

Figure 2. MODIS RSB calibration set up with the solar diffuser (SD) and the solar diffuser stability monitor (SDSM). The sunlight is reflected off the SD and to the SDSM and MODIS detectors via the scan mirror.

The calibration coefficient, m_1, is band, detector, sub-frame (for the sub-kilometer bands), and mirror side indexed. It is determined from SD observations, averaged over 50 frames and 20 scans per mirror side in each calibration,

$$m_1 = \left\langle \frac{BRF_{SD} \cdot \cos(\theta)}{dn^*_{SD} \cdot d^2_{E-S}} \cdot \Delta_{SD} \cdot \Gamma \right\rangle \tag{2}$$

where BRF is the bi-directional reflectance factor of the SD (characterized pre-launch), θ is the solar viewing angle, $d_{E\text{-}S}$ is the Earth-Sun distance at the time of the SD calibration, Δ_{SD} is the SD degradation factor derived from SDSM observations, Γ is the screen vignetting (transmission) function for the high gain bands with the attenuation screen in place, and dn^*_{SD} is the corrected solar diffuser digital response (DN_{SD}). The SD screen (SDS) vignetting function was characterized from two sets of on-orbit data collected during specially planned yaw maneuvers: one set of data with the SDS in place and another without the SDS.

2.2 Solar Diffuser Stability Monitor (SDSM)

The SDSM is used to monitor the solar diffuser's on-orbit degradation. During each calibration, it measures changes in the SD bi-directional reflectance factor (BRF) by successively viewing the illuminated SD, dark background, and the Sun. The SDSM has a spectral integrating sphere (SIS) with 9 filters and detectors covering wavelengths from 412nm to 936nm. These wavelengths are within the MODIS RSB spectral range. Table 1 shows the RSB bands (in the order of their spectral wavelengths) and the closely matched SDSM spectral bands.

Table 1. MODIS bands and corresponding SDSM bands

MODIS Bands	MODIS Center Wavelength (nm)	SDSM Bands	SDSM Center Wavelength (nm)
8	411.8	1	412.0
9	442.1		
3	465.6	2	465.7
10	486.9		
11	529.7	3	529.7
12	546.8		
4	553.7	4	553.8
1	646.5	5	646.1
13L	665.6		
13H	665.6		
14L	676.7		
14H	676.7		
15	746.4	6	746.6
2	856.7	7	856.5
16	866.2		
17	904.1	8	904.3
18	935.3		
19	936.1	9	936.2
5	1241.9		
6	1629.1		
7	2114.3		

The SD degradation is tracked by ratioing the near simultaneous SD and sun views from each SDSM detector, as depicted in Figure 2. A fixed attenuation screen is used for the SDSM's sun view so that the signals from the SD and the Sun are in the same range. The original approach of computing the degradation through a ratio of the SD view to the Sun view signal for each SDSM detector could not adequately determine the SD degradation due to a design error in the SDSM sub-system. The error caused the Sun view response to exhibit ripples (intensity variations across the scan of the SD) of up to 15%. Consequently a modified approach is used to determine the SD degradation by normalizing each of the detectors to SDSM detector nine[4,5]. Thus the SD degradation determined by the SDSM detector i is

$$\Delta^i = \left\langle \frac{dc^i_{SD} / dc^9_{SD}}{dc^i_{Sun} / dc^9_{Sun}} \right\rangle \tag{3}$$

where dc^i_{SD} and dc^i_{Sun} are the responses (in digital counts) of the ith SDSM detector to the SD view and the Sun view. This approach works since the SD's Spectralon™ has little degradation at 936nm. The normalization on a scan-by-scan basis substantially reduced the ripples in the Sun view response. The SD view response is corrected for the SD BRF. The SDSM's background is subtracted from its responses to the Sun and the SD. Other special considerations in the RSB calibration are reported in a number of references[6-8].

3. FOUR YEARS OF TERRA MODIS ON-ORBIT PERFORMANCE

The Terra MODIS was launched on December 18, 1999 and its nadir aperture door was opened on February 24, 2000. Since then there have been several spacecraft or MODIS related events and anomalies that have resulted in minor data gaps. In general, the instrument has been performing according to its design and continuously providing data for science studies and applications for more than 4 years. Table 2 summarizes the Terra MODIS operational configurations and some of the key events that have slightly impacted the RSB calibration continuity. This helps to explain some features in the calibration trending.

Table 2. Terra MODIS on-orbit operational events and anomalies

Day [Epoch 2000]	Anomaly Code	Event Description
218 (2000218)	Formatter anomaly	Formatter resets - transition to Standby Mode
232 (2000232)	Anomaly resolved	Transition to Science Mode (electronics A side)
305 (2000305)	B side electronics	Transition to Science Mode (electronics B Side)
	B side PS shut down	B-Side Power Supply shut down
549 (2001183)	A Side electronics	Transition to Science Mode (electronics A Side)
809 (2002078)	Safe Mode	Autonomous transition to Safe Mode
813 (2002082)	Science Mode	Transition to Science Mode
	Formatter anomaly	A-Side Formatter
991 (2002260)	B Side Formatter	Formatter switched from A to B side
1222 (2003126)	SDD anomaly	SDD failed to open during calibration
1279 (2003183)	Anomaly resolved	SDD to remain open for the rest of the mission
1446 (2003350)	Safe Mode	Transition to Safe Mode
1454 (2003358)	Anomaly resolved	Transition to Science Mode
1510 (2004049)	SFE anomaly	Science Formatting Equipment shut downs
1511 (2004050)	Anomaly resolved	Transition to Science Mode

3.1 Calibration Trending

The MODIS RSB calibration is performed for each band, detector, sub-sample (for sub-kilometer bands), and mirror side (BDSM indexed). Figures 3 shows the normalized calibration coefficients of Terra MODIS B9 and 17 (all detectors, mirror side 1) derived from over four years of SD on-orbit observations. Corresponding results from mirror side 2 are provided in Figure 4. A scaling factor has been applied to normalize the B-side coefficients to the A-side coefficients. The results show that the response changes are spectral band dependent and the differences among the detectors in each band are very small (less than 1% over 4 years). Depending on the spectral band, the rate of the response change of mirror side 2 is different from that of mirror side 1. On a detector-by-detector basis, the ratio of mirror side 1's response, to mirror side 2's response is shown in Figure 5.

Figure 6 depicts the normalized m_1 trending results for several RSB bands (3, 8, 9, 10, and 17; averaged over all detectors; mirror side 1) from their on-orbit SD calibration data sets. Obviously each band has its own trending behavior. Since no normalization is applied to the responses at different configurations in Figure 6, some of the major events listed in Table 2 can easily be identified. For example, the instrument started operating with A-side electronics at launch, switched to B-side electronics on October 30, 2000, and then switched back to A-side electronics (current configuration) on July 2, 2001 after the B-side power supply was shut down.

Figure 7 provides an equivalent response trending from lunar observations with the same RSB bands (mirror side 1). It shows similar response variations as in the SD calibration, indicating that some of the oscillating features in Figure 6 are not related to SD parameters and observations, and that they may be due to detector related gain changes.

Although the response derived from the lunar observations is very similar to that from the SD observations, the slope (change rate) of the lunar response is much larger than that of the SD response. This indicates the degradation of the scan mirror is angle of incidence (AOI) dependent since the SD and lunar results are derived from observations at different AOI to the scan mirror: the SD is at an AOI of 50.2° and the SV port is at 11.2°. Another on-board calibrator, the spectro-radiometric calibration assembly, can provide RSB response trending at a different AOI (38°) when it is operated in the radiometric mode. Its trending results are shown in Figure 8. Because of these temporal changes in the AOI dependent response, the L1B RSB calibration carries a time dependent RVS correction. Figures 3-8 show that the Terra MODIS RSB response is band dependent, mirror side dependent, and angle of incidence to the scan mirror dependent.

3.2 SD Degradation Trending

During on-orbit operation the SD bi-directional reflectance factor (BRF) degrades. The degradation is tracked on-orbit by the SDSM. The SD degradation followed a stable trend until an SD door related anomaly (May 2003) that eventually led to a decision to keep the SD door open with the SD screen in place for the remainder of the mission. Since then a new SD trend has been observed with a much faster degradation rate than in previous years. Figure 9 illustrates the SD degradation results derived from the SDSM observations.

The SD degradation trend is removed from the calibration coefficients via the parameter Δ_{SD} in Eqn. 2. The degradation is 1 at the time when the nadir door was open (mission day 2000055) and it does not account for any degradation that may have occurred between ground characterization and the first valid on-orbit SDSM observation. Prior to May 6, 2003, the SD degradation at wavelength of 412nm was up to about 10% for a period of 3.5 years. About a year later since the SD door anomaly, an additional 10% of SD degradation has occurred.

3.3 SD Screen Impact on the Calibration

The on-orbit RSB calibrations are performed using the SD/SDSM system. To avoid signal saturation an attenuation screen is used for the high gain bands (8-16). Figure 10 illustrates the calibration coefficients m_1 for bands 9 and 17 on a scan-by-scan basis determined from the SD calibration on day 2002268, prior to the SD door failure (see Table 2). Although a SDS vigneeting function is used in B9 calibration to reduce the screen impact, its calibration coefficients still show noticeable variations when compared to B17 that does not need the SD screen for its normal calibration.

Figure 11 shows another set of m_1 calibration coefficients for bands 9 and 17 from day 2003268 SD observations, one year apart from the calibration data sets used in Figure 10. This time the calibration coefficients for both B9 and B17 are derived with the SD screen in place (current fixed configuration), both showing similar variations due to the impact of the SD screen. The average over 50 frames in 20 scans of the calibration coefficients will substantially reduce the screen impact.

3.4 RSB Detector Noise Characterization

The Terra MODIS has been in operation for more than 4 years. There are 330 detectors for the 20 reflective solar bands. Except those identified pre-launch, only one detector has become noisy during instrument on-orbit operation. There are no inoperable detectors for the Terra MODIS RSB.

4. SUMMARY

In this paper we have presented a brief review of MODIS RSB on-orbit calibration approaches and provided long- and short-term trending examples of Terra MODIS (PFM) RSB responses from its more than four years of on-orbit operation. These results clearly show that the solar diffuser degradation has a clear wavelength dependency and that the sensor's response change is band (wavelength) dependent, mirror side dependent, and response versus scan angle dependent. Additional small changes in the calibration trend are likely due to instrument related events. These changes have been captured via LUTs applied to the L1B calibration to maintain the quality of its data products. With constant calibration efforts, the Terra MODIS instrument continues to operate well after four years, and is generating good quality Level 1B products.

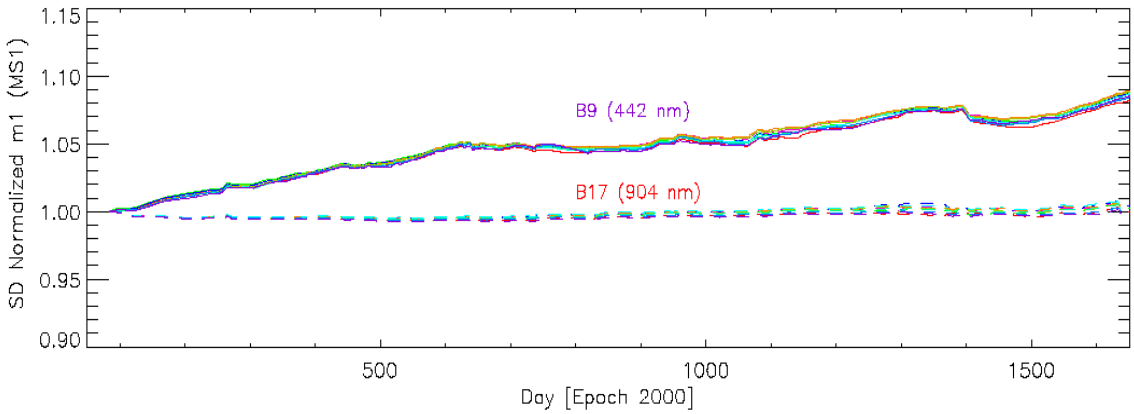

Figure 3. Detector response trending (all 10 detectors, mirror side 1) of reflective solar bands 9 and 17.

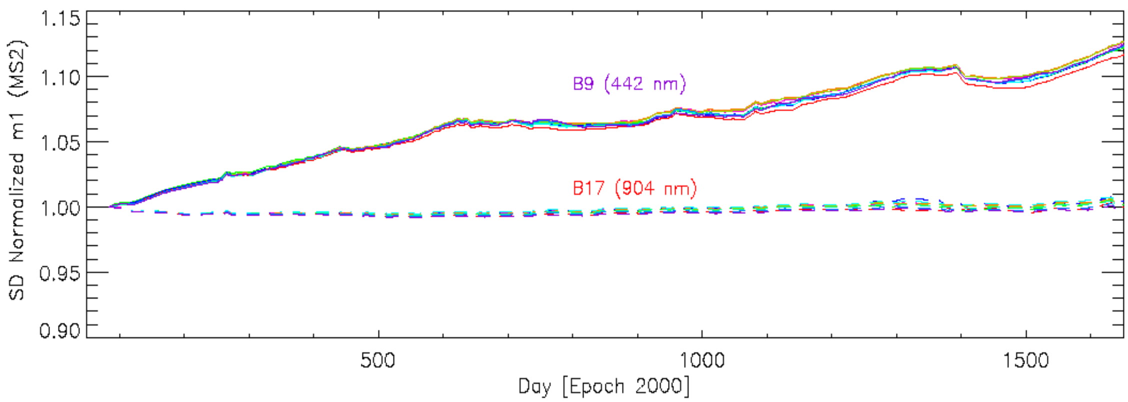

Figure 4. Detector response trending (all 10 detectors, mirror side 2) of reflective solar bands 9 and 17.

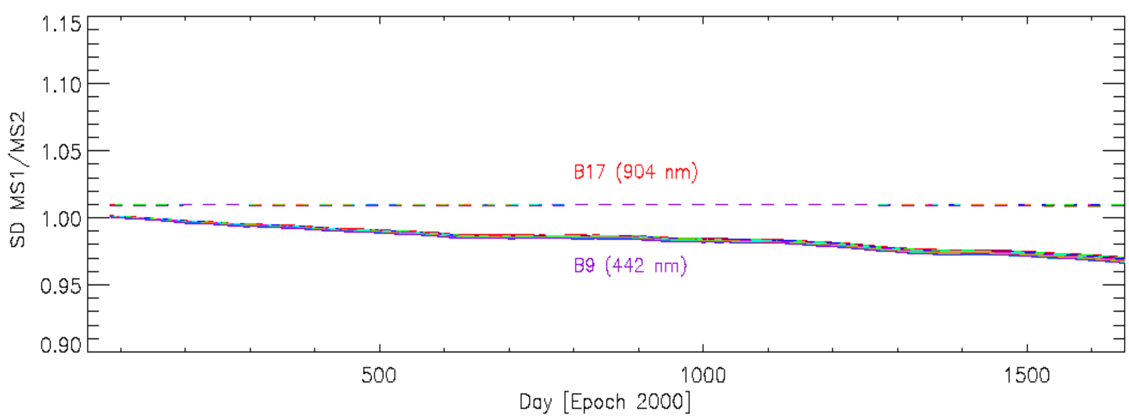

Figure 5. Ratios of mirror side 1 response (all detectors) to that of mirror side 2 for reflective solar bands 9 and 17.

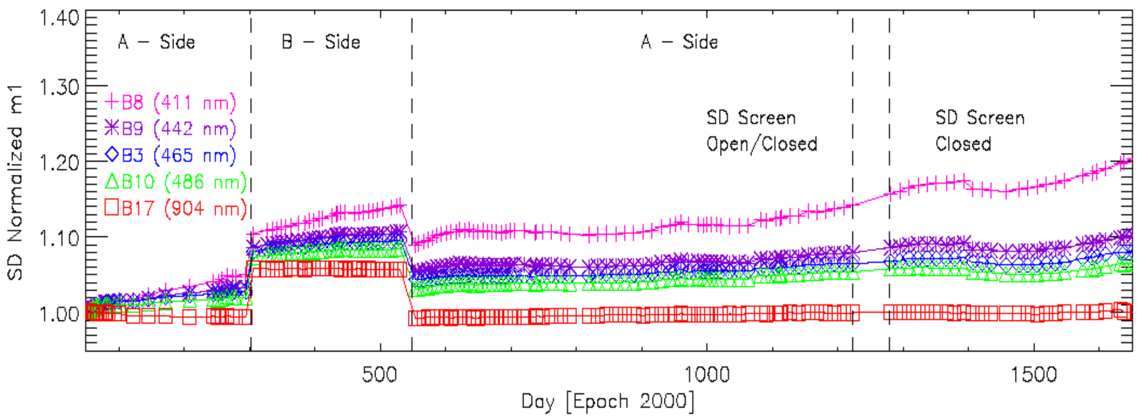

Figure 6. Reflective solar bands (8, 9, 3, 10, and 17) response trending from SD observations (averaged over all detectors in each band, mirror side 1).

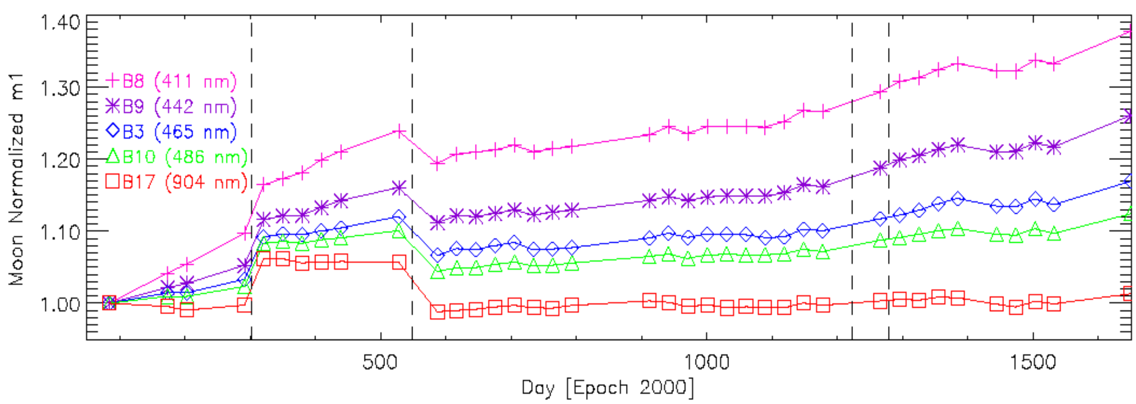

Figure 7. Reflective solar bands (8, 9, 3, 10, and 17) response trending from lunar observations (averaged over all detectors in each band, mirror side 1).

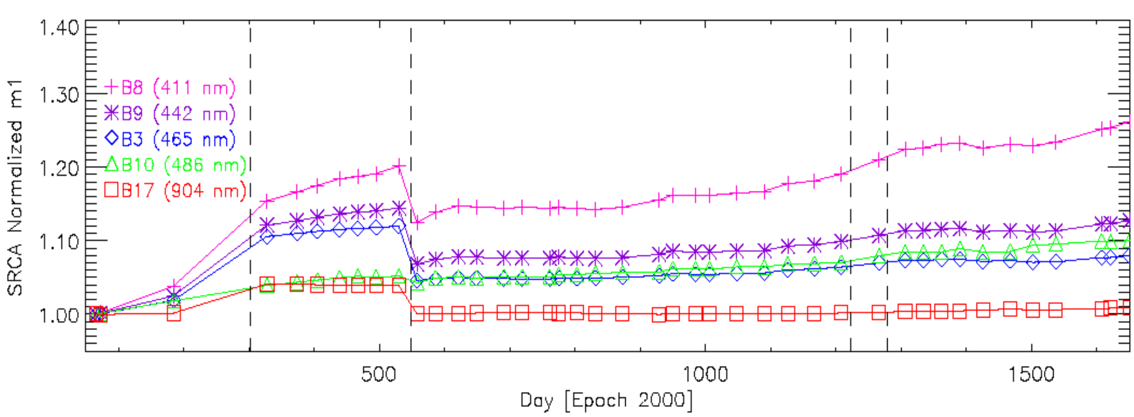

Figure 8. Reflective solar bands (8, 9, 3, 10, and 17) response trending from SRCA observations (averaged over all detectors in each band, mirror side 1).

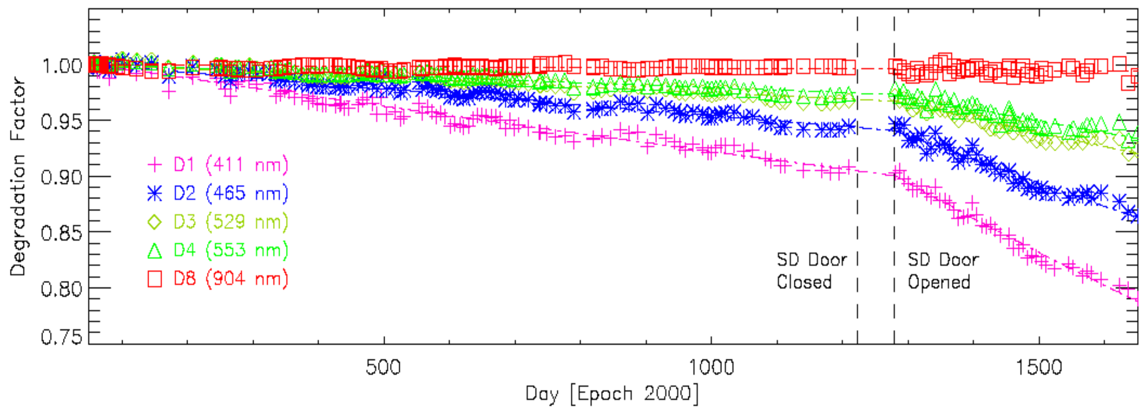

Figure 9. SD degradation factors (relative to SDSM detector 9) for SDSM detectors 1, 2, 3, 4, and 8.

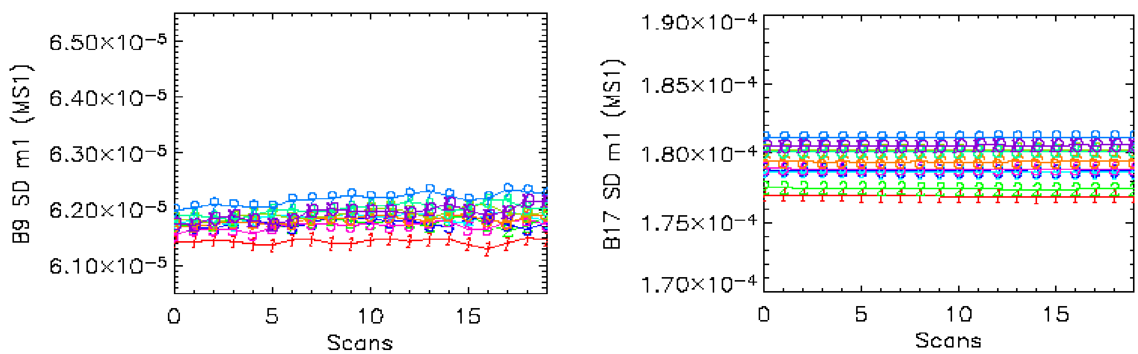

Figure 10. Short-term response trending of bands 9 and 17 on day 2002268 (all detectors, mirror side 1).

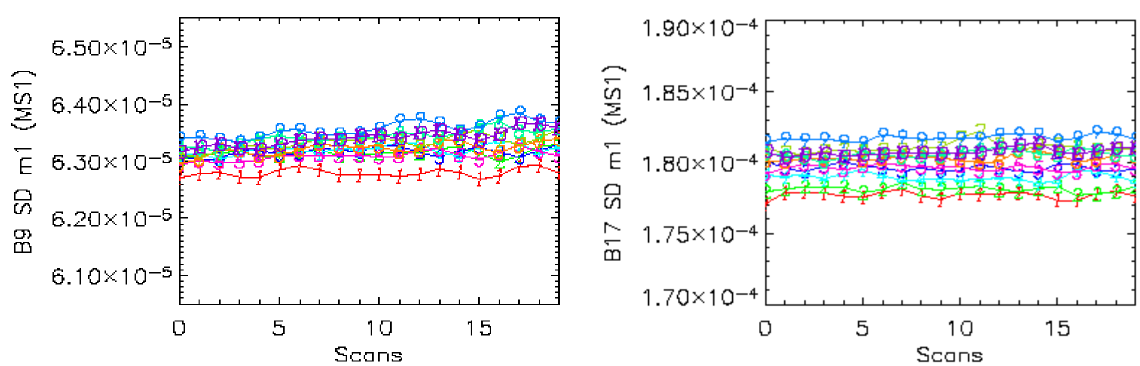

Figure 11. Short-term response trending of bands 9 and 17 on day 2003268 (all detectors, mirror side 1).

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